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An immersed structure approach for fluid-vegetation interaction

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A B S T R A C T

We present an immersed structure approach for modeling the interaction between surface flows and vegetation. Fluid flow and rigid and flexible vegetative obstacles are coupled through a local drag relation that conserves momentum. In the presented method, separate meshes are used for the fluid domain and vegetative obstacles. Taking techniques from immersed boundary finite element methods, the effects of the fluid on the vegetative structures and vice versa are calculated using integral transforms. Using a simple elastic structure model we incorporate bending and moving vegetative obstacles. We model flexible vegetation as thin, elastic, inextensible cantilever beams. Using the immersed structure approach, a fully coupled fluid-vegetation interaction model is developed assuming dynamic fluid flow and quasi-static bending. This relatively computationally inexpensive model allows for thousands of vegetative obstacles to be included in a simulation without requiring an extremely refined fluid mesh. The method is validated with comparisons to mean velocity profiles and bent vegetation heights from experiments that are reproduced computationally. We test the method on several channel flow setups. We calculate the bulk drag coefficient in these flow scenarios and analyze their trends with changing model parameters including stem population density and flow Reynolds number. Bulk drag models are the primary method of incorporating small-scale drag from individual plants into a value that can be used in larger-scale models. Upscaled bulk drag quantities from this method may be utilized in larger-scale simulations of flow through vegetation regions.

1. Introduction

1.1. Motivation

Flow in coastal regions is complicated by the presence of smaller-scale features including barrier islands, dykes, levees, and vegetated marshlands. Coastal vegetation, perhaps the smallest-scale of these features is one of the most important. The interaction of surface water flows and tightly packed beds of vegetation is an extremely complicated environmental process depending on many factors including water depth, vegetation height, vegetation thickness, vegetation flexibility, vegetation spacing, and flow velocity. The presence of vegetation affects surface flow by causing resistance to the flow, altering turbulence characteristics, attenuating waves, and increasing mixing. Flow resistance, mostly in the form of form drag, is the most important effect of vegetation on the large-scale flow.

Much of the effort in the numerical modeling of flow through vegetated regions has focused on developing turbulence closure schemes to the governing equations. There are two main approaches to providing turbulence closure. One method uses the Reynolds Averaged Navier–Stokes (RANS) equations, which requires a model for Reynolds stresses to provide turbulence closure. The other method uses Large Eddy Simulation (LES) turbulence models to solve the filtered Navier–Stokes equations.

RANS methods have been used with varying degrees of success. Christensen [1] found that simple mixing length closure methods can be successful models for flow through simple domains. However, Wilson and Shaw [2] acknowledge that first order RANS closure schemes, while simple, do not provide results that adequately match empirical data through more complex domains. They propose a higher order closure scheme for a spatially as well as temporally averaged version of the governing equations, resulting in a one-dimensional representation of the problem. Raupach and Shaw [3] extend this work, proposing a method of obtaining momentum and energy equations in multi-connected flows.

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These equations capture different momentum and dissipation terms resulting from the three-dimensional nature of this flow. Raupach et al. [4] validate this model experimentally, using aluminum strips to model vegetation.

The most commonly used RANS closure schemes are two equation methods. These schemes involve solving two transport equations for turbulent kinetic energy and dissipation whose solutions define an eddy viscosity. These equations contain empirically calculated constants. Burke and Stolzenbach [5] introduce drag-related source terms to model the effect of vegetation. The most commonly used two equation closure models are the k–ϵ and k–ω models. López and Garcia [6,7] give a full analysis of these schemes and show their ability to predict 3D flow patterns. Defina and Bixio [8] shows that a k–ϵ model may accurately predict flow patterns and eddy viscosities, but may poorly predict more complex turbulence characteristics.

As an alternative to RANS models, LES can be used to solve the filtered Navier–Stokes equations and can provide an almost complete description of the flow, while not requiring empirically derived transport equations to be solved. Early simulations of flow and turbulent structures above forests by Moeng [9], Shaw and Schumann [10], Kanda and Hino [11], and Dwyer et al. [12] show that important turbulence structures cannot be captured using a RANS model, but can be captured LES. LES of flow through vegetated channels is presented by Cui and Neary [13], Stoesser et al. [14,15] and Palau and Stoesser [16]. Mattis et al. [17] treat a bed of rigid vegetation as a porous medium and parametrize the drag coefficient in terms of nonlinear upscaling laws. In-depth analyses of turbulence statistics and temporally-averaged characteristics of these flows demonstrate the superiority of LES to RANS in capturing fine-scale flow qualities. However, LES may require significantly higher resolution than RANS.

The common approach for computationally modeling flexible vegetation is by treating a piece of vegetation as a flexible cantilever beam. Kutija and Hong [18] first proposed this method using standard Timoshenko [19] beam theory. Saowapon and Kouwen [20] developed a similar model. Darby [21] describes a one-dimensional model that may be used for both flexible and rigid vegetation. Erduran and Kutija [22] extend the work of Kutija and Hong [18] by using a 3D RANS technique with a combination of mixing length and eddy viscosity closure schemes. They propose quasi-3D coupling with the shallow water equations. Ikeda et al. [23] use cantilever beam theory and 2D LES to model "monami," the waving of flexible plants due to large eddies caused by instabilities in the flow field. They utilize a separate vegetation grid to track the movement of each piece of vegetation. Monami is explained and modeled in depth by Nepf and Ghialberti [24]. Velasco et al. [25] use classical beam theory to compute the displacement of flexible beams under small to moderate deflection. Kubrak et al. [26] extend the method developed by Kutija and Hong [18] for large deflections. Li an Xie [27] build off work involving stiff vegetation by Li and Zeng [28], add a thin plate of "foliage" to the stems and use a 3D LES scheme with a Smagorinsky closure model. They do not completely couple these models. Instead, they used a finite difference method developed by Al-Sadder and Al-Rawi [29] to solve the beam equation for a large variety of inflow velocities and performed a parameterization for the bent stem height based on flow velocity.

All of the above methods only consider planar bending; however in a flow with large velocity or much directional change or turbulence, we would not expect planar bending. Also, most of these models do not appropriately handle large deflections and are only valid for small deflections. They also tend to not be tightly coupled with the flow solver. We want to develop a method using cantilever beam theory to model flexible vegetation that is as robust and accurate as possible but is not overly computationally expensive.

1.2. Objectives

In this paper a new method for modeling fluid-vegetation interaction allowing flexible vegetative obstacles. We present a method for modeling the large deflection of individual vegetative obstacles as flexible cantilever beams. A robust numerical method for the beams using the finite element method is presented, verified, and validated against test problems. A thorough evaluation of computational expense is presented.

We present a method for coupling fluid flow with a large number of rigid and flexible vegetative obstacles. This method is an immersed structure method where separate meshes for the fluid and vegetative obstacles are used and ideas from fluid–structure interaction modeling are used to map the effects of one to the other. The method assumes a local drag model for individual vegetative obstacles. By using a simple local model, many more obstacles may be included than would otherwise be computationally viable; however, because of its simplicity it can only be expected to reproduce mean quantities. The method conserves momentum between drag in the fluid and the force required to bend obstacles. Validation is done through comparisons of mean velocity profiles of channel flow through tightly packed beds of rigid and flexible model stems. For flexible vegetation, average deflected heights are validated against experimental data.

An important application of the presented method is in calculating drag relationships that can be used in larger-scale models. Because we resolve fine-scale detail in a computationally viable way that preserves mean flow characteristics, it is ideal for upscaling. Bulk drag is the main method for quantifying the drag effects of a large number of obstacles packed together. It is discussed in detail in the following section. We use the method to calculate bulk drag coefficients for channel flows containing vegetative obstacles. Replicating the geometry of experimental setups as closely as possible, we reproduce trends for bulk drag relating to changes in velocity, spacing, and size that have been observed in experiments.

1.3. Bulk drag

One of the main effects that vegetation has on surface flow is resistance due to form drag. In this paper, we use the bulk drag coefficient of a bed of vegetation as the main quantity for comparison to experimental results. For a densely-packed vegetated channel, the amount of drag depends on many factors, including free-surface effects, turbulence, and complex velocity profiles. These effects are described in detail by Petryk [30]. Also, the presence of nearby vegetative obstacles affects the drag. As described by Nepf [31], for a vegetated channel, drag force per unit fluid volume is defined by the bulk drag equation

$$F_{drag} = \frac{1}{2}\rho \widetilde{C}_d a U^2 \quad (1)$$

where $\widetilde{C}_d$ is a non-dimensional bulk drag coefficient, ρ is the fluid density, U is the mean velocity, and a is the projected plant area per unit volume, the so-called vegetation population density. Modeling the plants as cylinders, a (per meter) is defined as

$$a = N_v D_v = \frac{D_v}{(\lambda)^2} \quad (2)$$

where N_v is the number of plants per unit horizontal area, D_v is the mean cylinder diameter, and λ is the mean spacing between plants.